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Technical Support Package

Analysis Method for Quantifying Vehicle Design Goals

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ANALYSIS METHOD FOR QUANTIFYING VEHICLE DESIGN GOALS

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D4OPS: DESIGN FOR OPERATIONS OF FUTURE REUSABLE LAUNCH SYSTEMS

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ABSTRACT

Designers of space launch systems should be cognizant of the impact of their design assumptions on operational characteristics. Operational metrics such as turnaround time, recurring cost, and headcount are critical factors for the future viability of such systems. The results presented here are from a study that seeks to determine in what manner design approaches can improve the operability of future space launch systems. This is accomplished by applying such operational approaches at the start of the concept design process. These design for operations (D4Ops) choices or approaches are determined from data-mining NASA Space Shuttle orbiter processing information. These approaches are then applied to three different launch vehicle contexts created for this study and based on existing NASA reference designs. These contexts include near (2010), mid (2015), and far (2025+) term examples. Specific lessons about the D4Ops approaches, as learned from the first two examples, are then applied to the far term context. Weighted rankings of the impact of these approaches on various metrics of interest are provided.

NOMENCLATURE

D4OPS	Design For Operations
DDT&E	Design, Development, Testing, And Evaluation
EDO	Extended Duration Orbiter
ETO	Earth-To-Orbit
FOM	Figure of Merit
LEO	Low Earth Orbit
MPS	Main Propulsion System
OPF	Orbiter Processing Facility
OSP	Orbital Space Plane
QFD	Quality Function Deployment
RCA	Root Cause Analysis
RLS	Reusable Launch System
SOP	State of Practice
SSTO	Single Stage To Orbit
STS	Space Transportation System
TOPSIS	Technique For Order Preference By Similarity To Ideal Solution
TPS	Thermal Protection System
TSTO	Two Stage To Orbit

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FORWARD

The operational characteristics of future Earth-To-Orbit (ETO) space launch vehicles (expendable and/or reusable) are key drivers that will determine program viability. Yet there seems to be lack of appreciation of this fact from the space launch vehicle design community, and specifically from the performance-oriented design disciplines. The goal of the Design for Operations (D4Ops) study is to make the performance-driven design community aware of the operational implications of their top level design choices on operationally driven Figures of Merit (FOM). The specific intended audience for this report includes both operations analysts and space system performance designers who are active in the conceptual or Pre-Phase A/Phase A stage of design. At this critical stage, top level parameters are being traded against each other in order to achieve an initial converged (and possibly optimized) design point. Future designs can hopefully incorporate lessons learned from operational experience.

INTRODUCTION

The Space Shuttle is an intricate machine, replete with various embedded subsystems in close proximity to each other that need careful scrutiny when being refurbished for the next flight. The Space Shuttle orbiter is processed in one of the three Orbiter Processing Facility (OPF) bays for approximately 80 calendar days (62 work days) with total mean integrated turnaround time of 159 days (OPF, Vehicle Assembly Building, and pad time)[1,2]. Such extensive processing has a direct impact upon the recurring cost of the Space Shuttle requiring a proportional increase in manpower and physical resources. The reasons for such processing requirements can be directly traced to the selection of subsystems on the architecture. Due to these selections in the early phases of design, optimistic predictions prior to the Shuttle's first flight of a large flight rate and subsequent low levels of processing have not materialized.

Often the designers of space launch systems do not concern themselves with the operational and economic impacts of their assumptions. Subsequently, there is scant linkage between appropriate subsystem technology choice and the impact on overall vehicle level metrics. Reductions in turnaround time and recurring cost increase mission availability resulting in a lower overall fleet size requirement. Operationally efficient space launch systems can be obtained through several possible paths: reduce capability, add more facilities and manpower, or design the architecture from the outset to be more operable.

OBJECTIVE

The Design for Operations (D4Ops) study was a 9-month effort concluding in January 2004 sponsored by the NASA Kennedy Space Center (KSC) Systems Engineering Office and undertaken by SpaceWorks Engineering Inc. (SEI)[3]. The goal was to begin quantifying the potential benefits of diverse new operational approaches in the conceptual design process. This was achieved through extrapolating insights (or approaches) gained from Space Shuttle processing experience that result in operational benefits and apply them to various future reusable launch system (RLS) case studies (or contexts). This process could reveal key compromises and trade-offs between weight, cost, operations, and safety when implementing new D4Ops approaches for different space vehicle configurations and operations. The resultant knowledge can help derive system designs for future space transportation systems that not only meet performance requirements, but which also do so affordably, safely, and at high flight rates. The authors seek to expand the intuition of conceptual launch vehicle designers to include operationally-oriented approaches. Performance-oriented designers should be cognizant, if even qualitatively, of the impact of their design assumptions on the ultimate metrics of the system.

The term “D4Ops approach” refers to a process or technology which can result in a potentially better operational system. One of the major objectives of this study was to develop a set of such approaches to be applied on various RLS contexts. D4Ops approaches can be classified as top-level system choices about the design (such as the total number of engines) or specific technology descriptions of various subsystems (such as the available types of Thermal Protection System material). The D4Ops approach generation process is meant as a starting point for examination of the D4Ops philosophy. Data-mining of the Space Shuttle Root Cause Analysis (RCA) database is a starting point in the identification of specific D4Ops approaches.

ANALYSIS PROCESS

For this study, these D4Ops approaches are applied to three different launch vehicle examples (or contexts). Typical "D4Ops approaches" include: reducing overall parts count, integrating functions across subsystems, eliminating hypergolic propellants, reducing numbers of tanks and fluids, etc. Most of the contexts are based on existing NASA reference designs and include near (first launch in 2010, Context 1), mid (first launch in 2015, Context 2), and far (first launch in 2025+, Context 3) term examples. Modeling and simulation then determine metrics that define the performance feasibility and economic viability of each context. A baseline system design is initially developed for the eventual application of such D4Ops approaches. Specific lessons about the merits of these D4Ops approaches, as obtained from the first two contexts, are applied to the far term context.

These D4Ops choices or approaches are determined from data-mining NASA Space Shuttle orbiter processing information. There is a substantial amount of raw data available that describes the quantitative aspects of processing the Space Shuttle (especially during the turnaround phase in the OPF). Examination of this data can reveal potential linchpins in such processing. This data originates from NASA's Root Cause Analysis (RCA) project that is continuing to document maintenance tasks on the Space Shuttle[4,5]. This database (in MS Access format) consists of various operations performed on the Space Shuttle Atlantis in the calendar years 1996 and 1997 encompassing missions STS-79 and STS-81 (with a majority of the data reflecting STS-81)[6,7].

Phase I of the project entailed of determination of the specific set of D4Ops approaches to be included in the analysis (see Fig. 1). A qualitative brainstorming discussion was initiated between SEI and NASA KSC Systems Engineering Office. The goal was to develop a long list of potential D4Ops approaches. This list was narrowed down through the use of the concurrent engineering process known as Quality Function Deployment (QFD). QFD is process whereby a qualitative prioritization of products, approaches, technologies can be generated through the scoring of attributes based upon the consensus opinion of a group of experts. Knowledge from the RCA database and brainstorming process resulted in 52 possible approaches. Weighted rankings resulting from the QFD process indicated ten relevant approaches. A qualitative determination was also made of the effort involved in conceptual level modeling of the above approaches. From the QFD process and additional discussions, an initial set of 11 D4Ops approaches was developed (detailed in Table 1). This number is reflective of an appropriate initial set of approaches that could be modeled given the scope of the study.

Phase II of the project applied the approaches on specific space launch architectures of interest (contexts): an Orbital Space Plane (OSP), Two-Stage-To-Orbit (TSTO) RLS, and a Single-Stage-To-Orbit (SSTO) RLS (see Fig. 2). These contexts were chosen based on NASA's current Integrated Space Transportation Plan (ISTP). The goal is to compare but not replicate previous analyses. A multi-disciplinary conceptual design environment comprised of in-house and government/industry standard tools was used to evaluate each context and determine weight, cost, performance, operations, reliability, and safety metrics that result from the application of the proposed D4Ops approaches. For Contexts 1 and 2, a baseline configuration, referred to as the state-of-practice (SOP) design, was designed without any of the D4Ops approaches (see Fig. 3). The numerical results were calibrated to information available from ongoing studies at NASA and from industry. The focus was not to be competitive, but to ensure the results are relevant.

For Contexts 1 and 2, once a satisfactory baseline was established, sensitivities were conducted on each of the 11 D4Ops approaches taken individually. In addition, a single roll-up of all applicable D4Ops approaches was conducted for each context (the 12th approach). A variety of performance, cost, safety, and operability metrics were determined for each of the twelve cases (11 approaches plus one roll-up). Using multi-attribute decision-making methods, the candidate D4Ops approaches were prioritized in terms of their potential to maximize an Overall Evaluation Criteria OEC) consisting of both performance (e.g. weight) and operationally related metrics (e.g. turnaround time). A series of weighting scenarios for the OEC were examined using the Technique For Order Preference By Similarity To Ideal Solution (TOPSIS) method. Examples of these scenarios include even weighting of all metrics, non-recurring cost centric, weight centric, cycle time centric, and safety centric. Finally, a median rank is calculated in an attempt to identify the best design approach across all weighting scenarios. Results of this analysis fed into the application of D4Ops approaches for Context 3.

CONTEXT 1: ORBITAL SPACE PLANE (OSP)

Introduction

A baseline near-term OSP context was developed similar to a crew transport vehicle under study by NASA Johnson Space Center (JSC). The near-term context (Context 1) was chosen as an Orbital Space Plane (OSP) vehicle of the type currently under consideration by NASA to fill the role of crew return and rotation to and from the International Space Station (ISS). The goal throughout the D4Ops study was to maintain focus on the enhanced operability design approaches and to avoid drawing undue attention to any particular vehicle context. In the case of the OSP context this meant examining the current design work on a wing-body OSP at NASA JSC and using this information to develop a similar, though not identical, vehicle architecture for use in the D4Ops research. Thus the baseline near-term context does not attempt to represent a “better” OSP design, but rather a comparable and relevant context in which D4Ops design approaches can be evaluated (see Fig. 4).

State-Of-Practice Design Summary

The baseline or state of practice (SOP) near-term Context 1 was modeled using industry standard tools and conceptual design methods. The scope of the design process was limited to the OSP stage and the crew escape system (CES), and did not include the Evolved Expendable Launch Vehicle (EELV) required to boost the OSP to its initial orbit. By adhering to a very similar set of design assumptions to that used by the OSP program at NASA JSC, it was possible to produce a near-term OSP context that was comparable and relevant. Critical assumptions regarding mission parameters, configuration, propulsion, structures, thermal protection system (TPS), power generation, and environmental control and life support (ECLS) were similar to the JSC "winged" OSP design as of April, 2003. The SOP Context 1 vehicle geometry and packaging interior layout shows notional placement of various major subsystems including OMS propulsion, RCS propulsion, primary power, crew accommodations, ECLS, and the recovery system. Sizing analysis for the SOP Context 1 resulted in a vehicle dry weight of 39,218 lbs, and gross weight of 55,665 lbs including the CES (see Fig. 5). Cost, safety, and operational metrics were also determined for the Context 1 SOP for later comparison with D4Ops approaches.

The Context 1 SOP was developed as a baseline for application of each of the eleven individual D4Ops design approaches and eventually for a roll-up design incorporating all of the D4Ops approaches that could be accommodated simultaneously. Fig. 6 illustrates the application of the D4Ops approaches to the baseline context and Fig. 7 reveals the impact upon the overall weighted output metrics.

Results of D4Ops Approaches on Context 1

Approach 1 (Reduce Parts) resulted in the lowest dry weight, Approach 3 (All Electric) gave the lowest Design, Development, Testing, and Evaluation (DDT&E) cost, and Approach 12 (Roll-up) offered the shortest total cycle time even with a weight penalty. Approaches 12, 5, and 10 placed first, second, and third respectively when the median ranking across weighting scenarios was performed. The success of Approach 12 (Roll-up) in the final ranking indicates that the advantages of enhanced operability design approaches can outweigh their real or perceived penalties. Approach 12 can, in spite of its high initial cost, achieve a cumulative life cycle cost much lower than the baseline due to reduced operational costs. The common threads among the three top ranked approaches seem to be integrating tankage among subsystems, and using safer, more benign fluids for propulsion and power. Just reducing parts count or the number of engines may be necessary but not sufficient for producing the best overall design. Also, it appears that employing selectively uniform TPS has the potential to significantly improve the operability of a design.

The cost benefit of applying these D4Ops approaches emerges as the life cycle of the program progresses. Fig. 8 illustrates how the cumulative life cycle cost for each of the design approaches compares with the SOP Context 1. The context with all 11 approaches costs more in the beginning of the program (relative to the SOP). Yet as the program progresses the higher initial hardware costs for these approaches are offset by reduced operational costs.

The improvements attained by incorporating D4Ops approaches were limited by the constraint of only examining one portion of the architecture (namely the

OSP). The results of the analysis on Context 2 later support this conclusion. The D4Ops approaches add weight penalties to the OSP Context, possibly as high as 10%, in exchange for significantly improved operational metrics. This indicates that future designs should emphasize a reduction in parts count and improvement in component/system/sub-system to allow reduced redundancy (weight) at equal or improved levels of safety. Future work into new development processes, manufacturing systems, and organizations for the creation of low volume, complex, and reliable systems is urgently needed to reduce DDT&E and Theoretical First Unit (TFU) costs.

CONTEXT 2: TWO-STAGE-TO-ORBIT RLS

Introduction

A baseline mid-term TSTO context similar to architectures under study by NASA was developed (See Fig. 9 and Fig. 10). For the purposes of this study "mid-term" was considered to mean a vehicle whose initial operating capability (IOC) occurred around 2015. In the interest of establishing a comparable and relevant context, the study authors reviewed the design work conducted by NASA as part of the Next Generation Launch Technologies (NGLT) program on a mid-term, TSTO architecture. This vehicle concept was identified as NGLT Architecture 5 at the time the study was conducted. Using the NGLT Architecture 5 concept as an example, a similar, but not identical, TSTO vehicle was developed by SEI to serve as a mid-term context. Unlike the near-term Context 1, Context 2 was a complete end-to-end system that required iterative vehicle performance closure to analyze each design approach.

State-Of-Practice Design Summary

The baseline mid-term Context 2 was modeled using an expanded set of conceptual design tools beyond those required for Context 1. Since the scope of the design process encompassed an entire ETO launch system, a vehicle closure process involving trajectory simulation and weights/sizing was required to quantify the impact of an approach. This mid-term TSTO baseline concept possessed comparable performance to the NASA NGLT Architecture 5 TSTO. Critical assumptions regarding mission parameters, configuration, propulsion, structures, TPS, and primary power were similar to the Architecture 5 design as of October, 2003.

The interior layout shows notional placement of various major subsystems including OMS propulsion (orbiter stage only), RCS propulsion, primary power, avionics, and thermal control. Sizing analysis for the SOP Context 2 resulted in a booster dry weight of 472,856 lbs, an orbiter dry weight of 184,737 lbs, and a total system gross weight of 4,290,683 lbs (See Fig. 11 and Fig. 12). Cost, safety, and operational metrics for the Context 2 SOP were also determined for later comparison with D4Ops approaches.

The Context 2 SOP was developed as a baseline for application of each of the eleven individual D4Ops design approaches and for a roll-up design incorporating all of the D4Ops approaches that could be accommodated simultaneously. Fig. 13 and Fig. 14 illustrate the application of the D4Ops approaches to the baseline context with Fig. 15 revealing the impact upon the overall weighted output metrics.

Similar to Context 1, a cumulative LCC comparison was performed. Fig. 16 illustrates how the cumulative life cycle cost for each of the design approaches compares with the SOP Context 2. The Roll-up with all 11 approaches (Approach 12) costs more in the beginning of the program (relative to the SOP). Yet as the program progresses the higher initial hardware costs for these approaches are offset by reduced operational costs. Unlike Context 1, as the program progresses the LCC of Approach 12 still remains above the SOP as the high initial cost difference for Context 2 takes longer to overcome.

Results of D4Ops Approaches on Context 2

Approach 9 (Less Aeroshell) resulted in the lowest dry weight, Approach 3 (All Electric) gave the lowest DDT&E cost, and Approach 12 (Roll-up) offers the shortest total cycle time. Although Approach 12 attained the best overall cycle time, its poor performance in terms of both weight and non-recurring cost led to a low final ranking. Approaches 10, 9, and 8 placed first, second, and third respectively when the median ranking across weighting scenarios was performed. It is interesting to note that Approach 10 (Common Fluids/Tanks for Propulsion/Power) appears among the top three approaches for both the near-term Context 1 and mid-term Context 2. Approach 9 (Less Aeroshell) was more influential when applied to Context 2 than

Context 1 because in the case of Context 2, the iterative vehicle closure process allows the weight reduction to propagate through both stages of the vehicle. For instance, reducing aeroshell on the orbiter stage has the effect of reducing the weight on both the booster and orbiter when the vehicle is re-closed. Approach 8 (Propulsion-Integrated Vehicle Health Management or P-IVHM) ranks third in the median rankings due to the fact that it provides moderate operational benefits with a small weight penalty. Unlike the near-term Context 1, the commonalities between the top ranking approaches are less obvious in Context 2. Approaches 10, 9, and 8 occupy the top three spots in both the safety focused weighting scenario and the DDT&E and Ground Support Equipment (GSE) focused scenario. These observations suggest that design approaches that tend to reduce exposure to hazardous fluids or closed compartments have the greatest effect on improving operational metrics.

CONTEXT 3: SINGLE-STAGE-TO-ORBIT RLS

Introduction

The final contexts in which a set of D4Ops design approaches were evaluated were a pair of advanced, far-term architectures. For the purposes of this study "far-term" was taken to mean a vehicle whose IOC was around 2020. Discussion between study participants, the authors and personnel at NASA KSC, led to changes in the implementation of the D4Ops process for Contexts 3a and 3b. First of all, unlike Contexts 1 and 2, 3a and 3b would not be based on any particular existing design study. Secondly, instead of developing a baseline Context and then applying D4Ops design approaches one by one as done previously, Contexts 3a and 3b would incorporate D4Ops thinking from the beginning. It was decided that modifications to the initial list of eleven D4Ops design approaches should be made before proceeding to the far-term context analysis (see Table 2). The authors reviewed the list of ideas conceived during the initial D4Ops brainstorming session and reviewed operational design recommendations published by the Space Propulsion Synergy Team (SPST). Several new D4Ops approaches were subsequently added to the original eleven, while some of the existing approaches were combined.

Context 3a Design Summary

A variety of far-term architectures were considered before selecting the configuration seen in Context 3a (see Fig. 17). Major attributes such as number of stages, type of propulsion, take-off orientation, landing orientation, propellants, and mission were discussed. The array of options was qualitatively evaluated based on D4Ops design principles and lessons learned from Contexts 1 and 2. The outcome for Context 3a was a fully reusable, all-rocket SSTO that takes off vertically and lands horizontally (see Fig. 18). The design includes a high degree of TPS shape commonality, all-electric actuation, and the notion that the aft face of the vehicle is not covered by an aeroshell. The Main Propulsion System (MPS) is easily accessible, and is designed to operate at 90% of its design power level during ascent to increase design life. These main engines will also be deeply throttled for use in orbital maneuvering. Fig. 19 identifies the D4Ops approaches incorporated in Context 3a.

The reference mission was based loosely on the DARPA Operational Responsive Spacelift (ORS) Force Application and Launch from CONUS (FALCON) requirements. From the DARPA specifications a payload of 12,000 lbs to a 100 nmi. circular orbit at 28.5 degrees was chosen for Context 3. The vehicle performance closure for Context 3a and 3b was slightly different from that of Context 2. The primary difference was that Context 3a and 3b were simulated with variable mixture ratios throughout the ascent phase to improve gross weight values (see Fig. 20).

Context 3b Design Summary

The original intention had been to develop and analyze a single Context 3 vehicle using D4Ops approaches from the beginning of the design. However, after completing work on the first far-term vehicle, Context 3a, several interesting design approaches still had not been fully investigated. In particular, the idea of modular design had not previously been implemented and its benefits and costs were not known. There was also a desire to see a more extreme implementation of the reduced aeroshell approach since this strategy had produced favorable results on the other contexts. Context 3b was developed in response to these unanswered questions (see Fig. 21).

Brainstorming for Context 3b resulted in several design architecture ideas. First, the use of modular pallets to carry the main propellants was discussed. Conceptually these pallets would resemble the Extended Duration Orbiter (EDO) pallets used occasionally on the Space Shuttle. Preliminary examination of the packaging of such pallets in a far-term single stage vehicle proved that such an idea was not feasible. Another initial Context 3b design called for a fuselage whose upper surface (aeroshell structure) could be detached and lifted off during maintenance. Doing so would enable technicians to perform maintenance and inspections without the need to purge closed fuselage compartments. However, this concept was also set aside because it was perceived as only a small departure from the Context 3a vehicle.

The Context 2 design showcases both the modularity and reduced aeroshell approaches (see Fig. 22). The main fuel and oxidizer are stored in conformal tanks that are assumed to be removable during normal ground operations. Since the fuselage has only limited aeroshell structure to protect the tanks, their exposed surfaces are covered by TPS blankets. The tight packaging of the propellant tankage allowed Context 3b to be considerably smaller and lighter than Context 3a while still performing the same mission of delivering 12,000 lbs to Low Earth Orbit (LEO). Fig. 23 identifies the D4Ops approaches incorporated in Context 3b.

Results of D4Ops Approaches on Context 3

The objective of Context 3 was to attempt to use D4Ops principles from the outset of a new, far-term vehicle design. The hope was that by applying the conclusions and lessons learned from Contexts 1 and 2 the authors would be able to act on the idea of designing for operations. The experience gained in the course of the conceptual design process resulted in several important conclusions. First and foremost, the fact that old habits are hard to break was made evident early on in the Context 3 analysis. Although the authors set out to use D4Ops from the very beginning, it was found that key early design decisions were based on past experience and specifically performance-based reasoning. Traditional conceptual vehicle design begins with a mission requirement such as payload to LEO or number of passengers to a moon colony. What D4Ops process suggests is that along with this mission requirement a corresponding operational design goal should be established at the start. For instance, instead of simply dictating that Context 3a and 3b would be vertical take-off, horizontal landing, rocket-powered vehicles, the process should have begun with a D4Ops-derived operational goal (such as the vehicle shall have the minimum practical number of fluids and tanks). The combination of mission requirements and operable design requirements could then have been allowed to drive out a particular vehicle architecture and geometry.

The authors also learned more specific lessons about the concept of modularity in conceptual vehicle design. During the brainstorming sessions that preceded the development of Context 3, the idea that modular vehicle systems might enhance operability gained support. What was interesting was to watch how the implementation of modular design evolved in the Context. Early thoughts that the main propellant tanks could be designed to resemble the Space Shuttle EDO pallets were dismissed when faced with the geometric reality of accommodating the required fluids. Then when thoughts turned to dividing the main propellant volume into smaller cylinders that could presumably be removed through an opening in the aeroshell, the perceived operational benefits seemed to evaporate. Only when the modular approach was mated with the conformal tanks and deleted aeroshell was the anticipated result achieved. Perhaps the greater lesson to be learned from the modularity experiment is that had the vehicle configuration and geometry not be predetermined before thoughts of D4Ops approaches were put into action, the question would not have been "How do we make modularity work on this architecture?" but rather "What architecture will enable the best implementation of modularity?" The answer to the second question reflects the inherent characteristics of a D4Ops philosophy.

CONCLUSIONS

General Observations

Relevant findings derived from this study include:

- The D4Ops approaches chosen for this study had a wide variety of impacts on the system.
- Application of most of these D4Ops approaches result in systems that performed better operationally (in terms of lower recurring operations cost per flight and turnaround time) at

a cost of having worse performance. Application of these approaches generally resulted in systems with heavier dry and gross lift-off weights (GLOW) that required more development funding with higher flight unit acquisition costs.

- While many D4Ops design features do impose performance (i.e. weight) penalties, some approaches can provide operational benefits with only slight performance penalties.
- The D4Ops approaches chosen for this study were developed through a combination of qualitative and quantitative processes.
- It took extensive time and effort to develop and apply the first foundations of such a D4Ops intuition. As more contexts were examined, this process became easier. As the project progressed the study group was more and more concerned about using the D4Ops design intuition that was developed from each previous Context. Thus by Context 3 this study group was readily cognizant of the impact of certain design decisions upon operational metrics of interest. For example, as the project further progressed the impact of reducing to a complete battery power storage system became apparent. Yet even at the end of the study, there was still some hesitancy in taking the D4Ops philosophy to its logical conclusion.
- The portion of the RCA database used in this study, based upon Space Transportation System (STS) orbiter processing information from NASA KSC, has some data integrity issues. The work hours in the database may not be reflective of actual man hours on each task. The data should be updated to reflect both the breadth of missions (currently only includes data mainly for the STS-81 flight) and the depth of work required all throughout the organization for such a flight.
- Constraints were imposed by the pre-selection of Contexts 1 and 2. The top level architecture assumptions inherent in these two contexts, OSP and TSTO RLS, precluded some approaches from being applied. Conversely, this actually may have been beneficial in order to show the discrepancy of current performance-oriented design intuition and the influence of a D4Ops-oriented approach.
- Even given flexibility in choosing Context 3, it was potentially too constrained to be able to handle all of the D4Ops approaches developed from the RCA database.
- It is recognized that the Context 3 RLS is an easier concept to operate given the single stage nature of the architecture. There is no implication made here that such SSTO systems are the most optimum. The SSTO option was chosen to include a vastly different context than that seen in Contexts 1 and 2.
- Design discussion and data transfer issues were made easier by the co-location of both performance and operations discipline experts in the same geographic area (as performed by the authors, located at the same organization).
- The conceptual level toolset is limited in its ability to model certain D4Ops design approaches.
- Reducing the number of fluids carried on a RLS is beneficial to its operability.
- Given the extensive nature of some of the D4Ops approaches on nearer term Contexts 1 and 2, it is speculated that adding such approaches to the current Space Shuttle orbiter would be very difficult and potentially vastly expensive.

Recommendations and Future Work

Recommendations resulting from this study include:

- The results of this study should be used to integrate the D4Ops design intuition philosophy into the current conceptual design process. This could include education of the performance-oriented discipline experts of the impact of their design assumptions on operational FOMs.
- Better modeling capability should be developed to handle different operational approaches than those currently used on the Space Shuttle. There may be a need to examine the entire operational flow process for these contexts (from landing to launch) to better account for the impact of D4Ops approaches.
- Future analyses using the D4Ops philosophy should examine contexts from the same time frame for more accurate comparison of D4Ops approaches.
- Additional D4Ops approaches can be developed using similar methods of brainstorming and prioritization as described in this study.
- The RCA needs to be updated with additional data gathering and mining.
- There may be a potential to examine a more revolutionary use of the D4Ops philosophy in the design process. There may be some follow-

on activity from this project that could examine how the execution of the operations discipline could be moved forward in the design process, feeding some portion of the performance closure loop. In this scenario, the operations discipline could actually help determine vehicle level characteristics such as the geometry including the outer mold line (OML).

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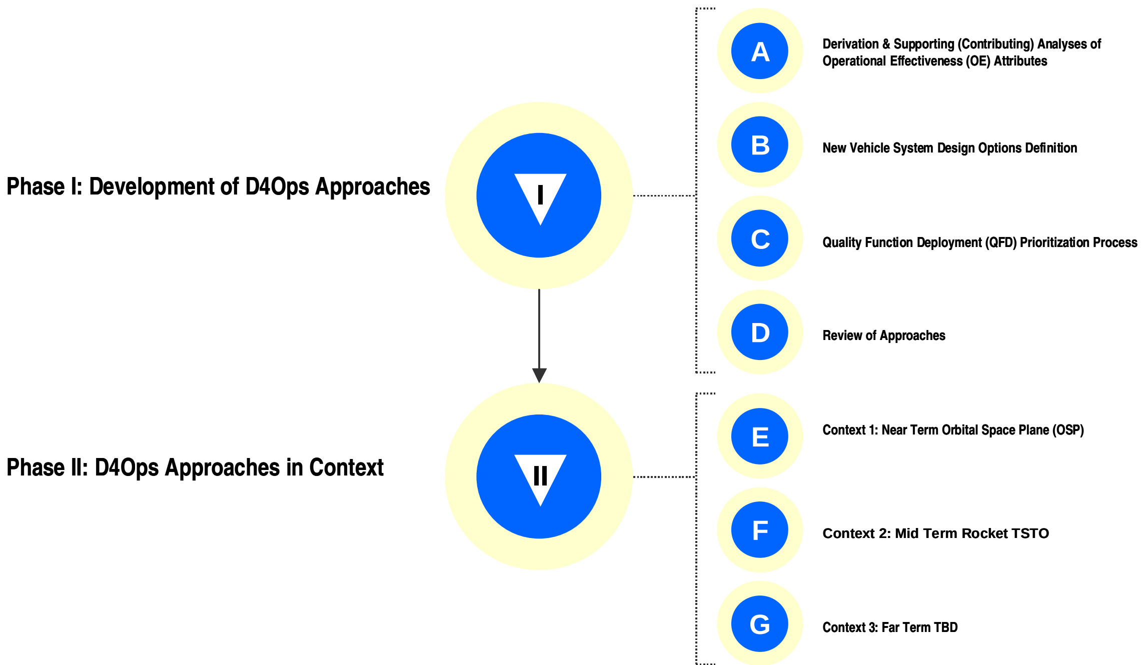
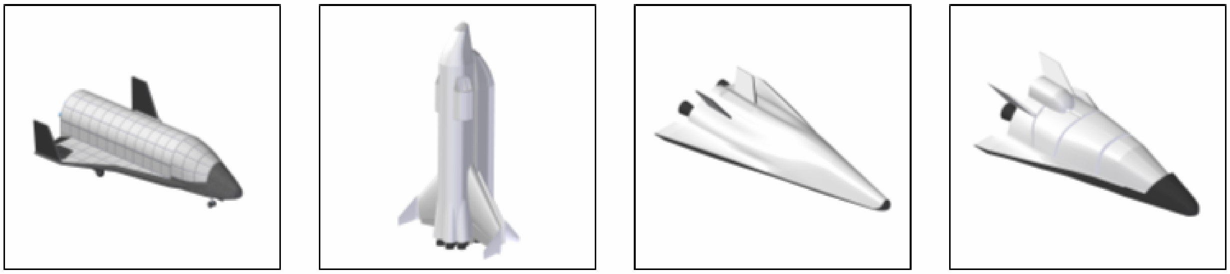


Fig. 1: Overview of D4Ops Project.

Design4Ops Strategy	Work Content Potential Reduction Through Use of D4Ops Strategy (Total RCA Direct Work Contribution)	Selected Design Approach
INTEGRATE PROPULSION SYSTEMS	Liquid Propulsion Work Content (14.5% Max Contribution)	Reduce engine count (use larger, fewer engines for main/OMS/RCS, i.e. Eliminate need for separate OMS engines by using throttled MPS on-orbit)
		Eliminate all hypergols in favor of LOX/LH2 propellant combination for ACS
		Eliminate hypergols AND cryogenic ACS propellants in favor of "green" non-cryogenic ACS propellants
		Incorporate Propulsion-focused IVHM
INTEGRATE POWER MANAGEMENT FUNCTIONS	Power Management Work Content (10.9% Max Contribution)	Simpler, all-electric power and actuation system (use EMAs/EHAs at load and use high storage density batteries in place of fuel cells and APU's, replace plumbing with wiring)
IMPROVE PASSIVE THERMAL MANAGEMENT	Thermal Management Work Content (10.7% Max Contribution)	Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces
		Reduce TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals)
INTEGRATE ACROSS PROPULSION & AIRFRAME	Liquid Propulsion/Structures, Mechanisms & Veh Handling (48.2% Max Contribution)	Eliminate external aeroshell and closed compartments, Integrate structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.
INTEGRATE ACROSS PROPULSION & POWER FUNCTIONS	Liquid Propulsion/Power Mgmnt (25.4% Max Contribution)	Use common fluids AND tanks for Main Propulsion System, OMS, RCS and Power
INTEGRATE ACROSS PROPULSION, PWR & THERMAL MGMNT FUNCTIONS	Liquid Prop/Power/Thermal Mgmnt (36.1% Max Contribution)	Use common fluids and tanks for Main Propulsion System, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics, and ECLSS)
INCREASE OVERALL SYSTEMS RELIABILITY	Unplanned Work Content (24% Max Contribution)	Reduce parts count using highly reliable parts (vs. less reliability in the parts and higher need for redundancy as in Shuttle)

Table 1: Initial Set of D4Ops Approaches.



Context 1 Context 2 Context 3a Context 3b

Fig. 2: Sample Design Contexts for Operational Approaches.

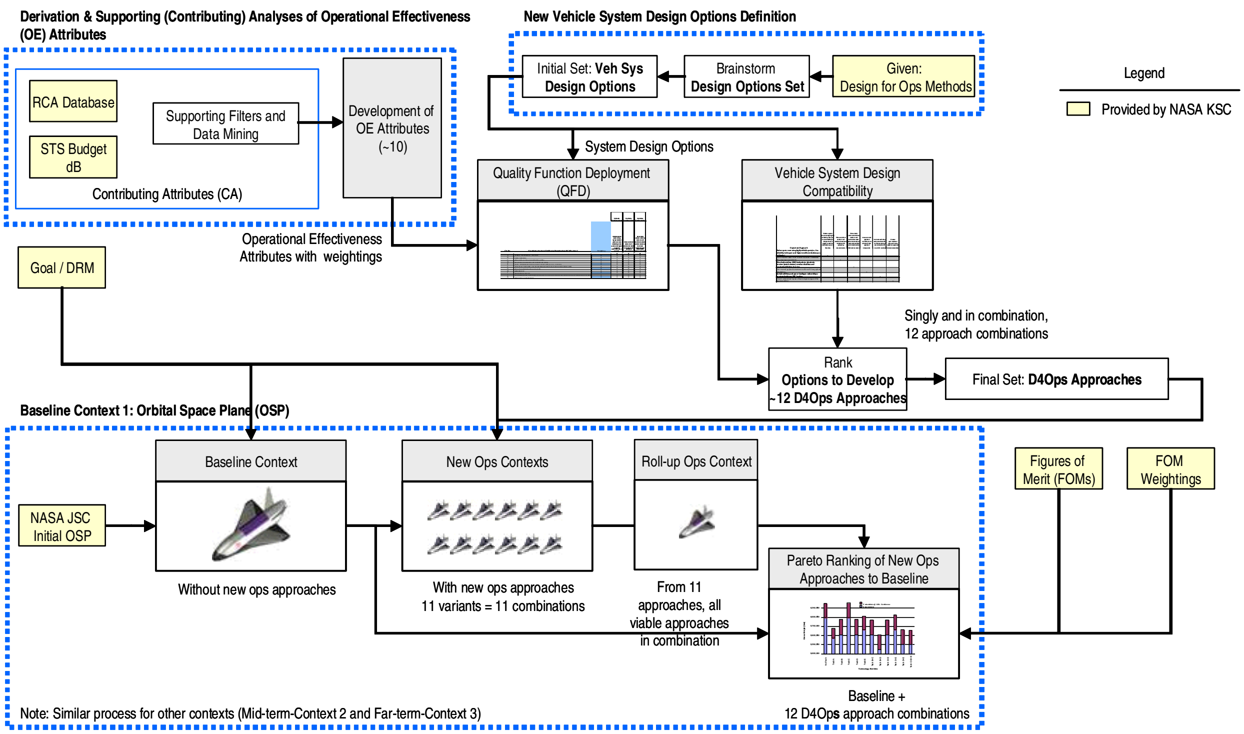
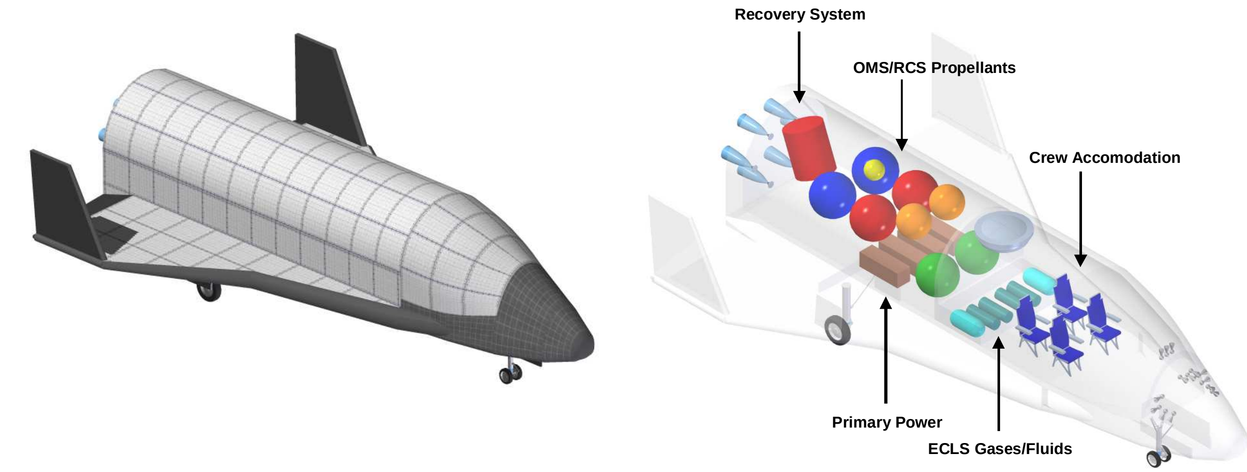


Fig. 3: Schematic of D4Ops Approach (For Context 1).



External View Internal Packaging View

Fig. 4: D4Ops Context 1: Design Approach 0 (State-of-Practice).

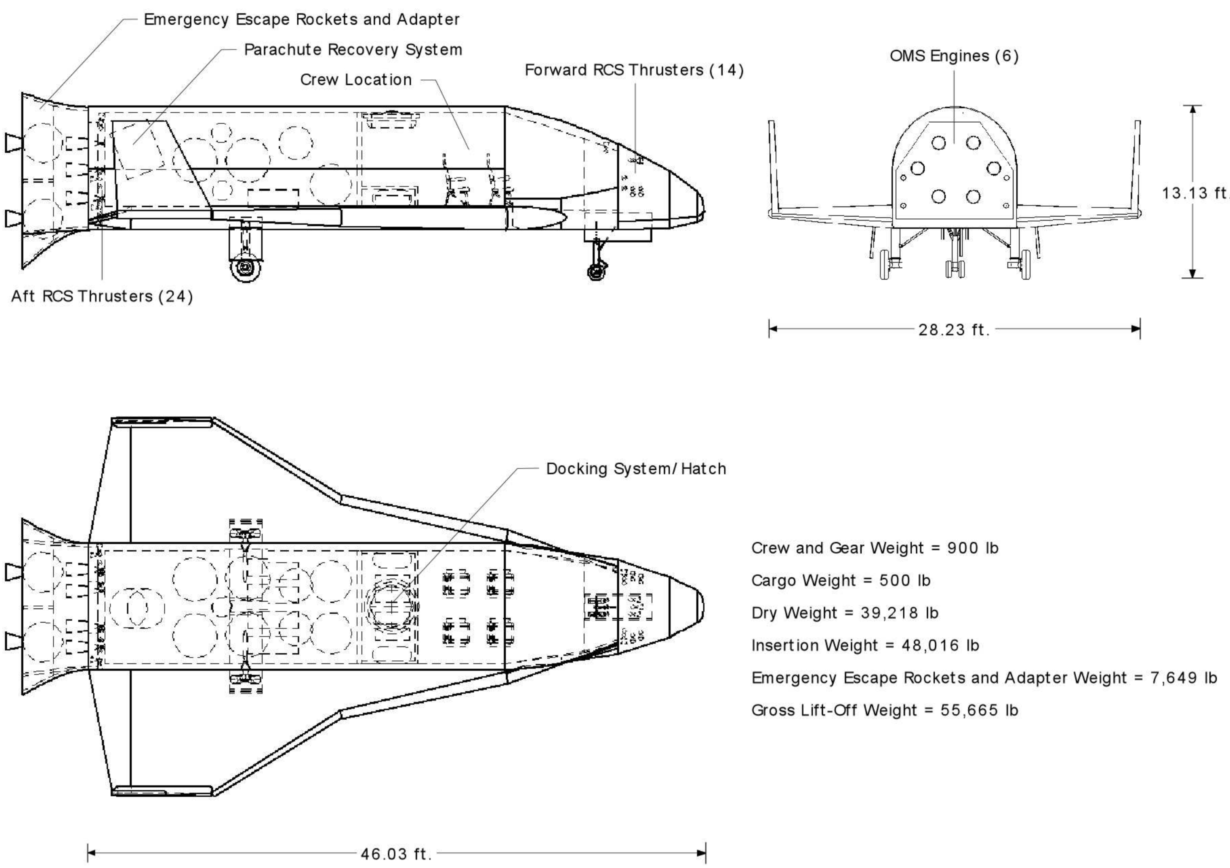


Fig. 5: Context 1 Three View: Design Approach 0 (State-of-Practice).

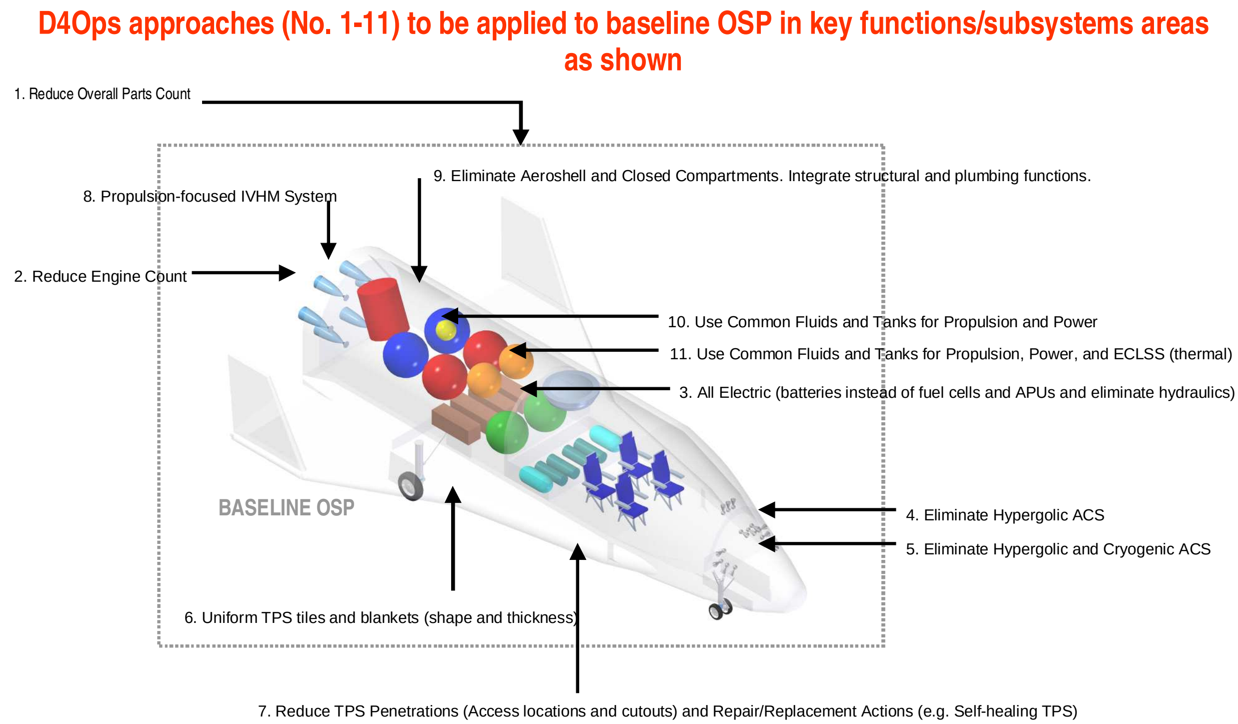


Fig. 6: Context 1: D4Ops Design Approaches to Be Added.

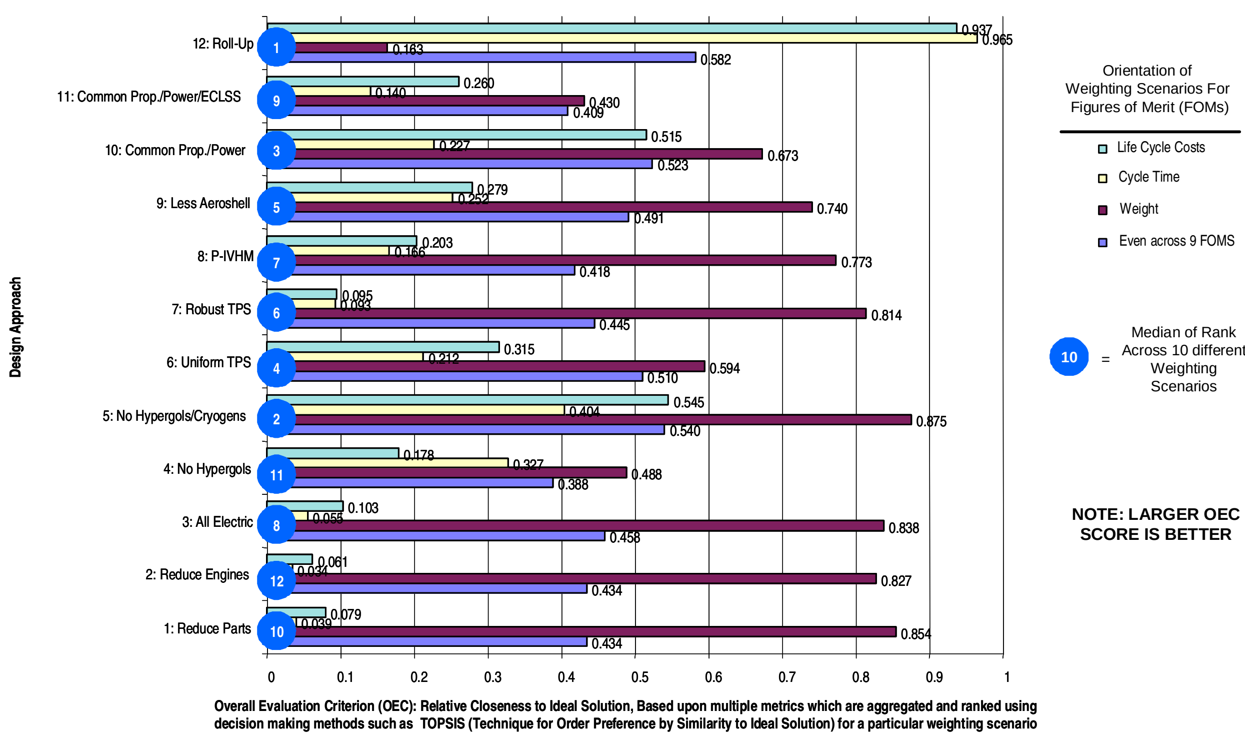


Fig. 7: D4Ops Context 1: TOPSIS Ranking of Design Approaches.

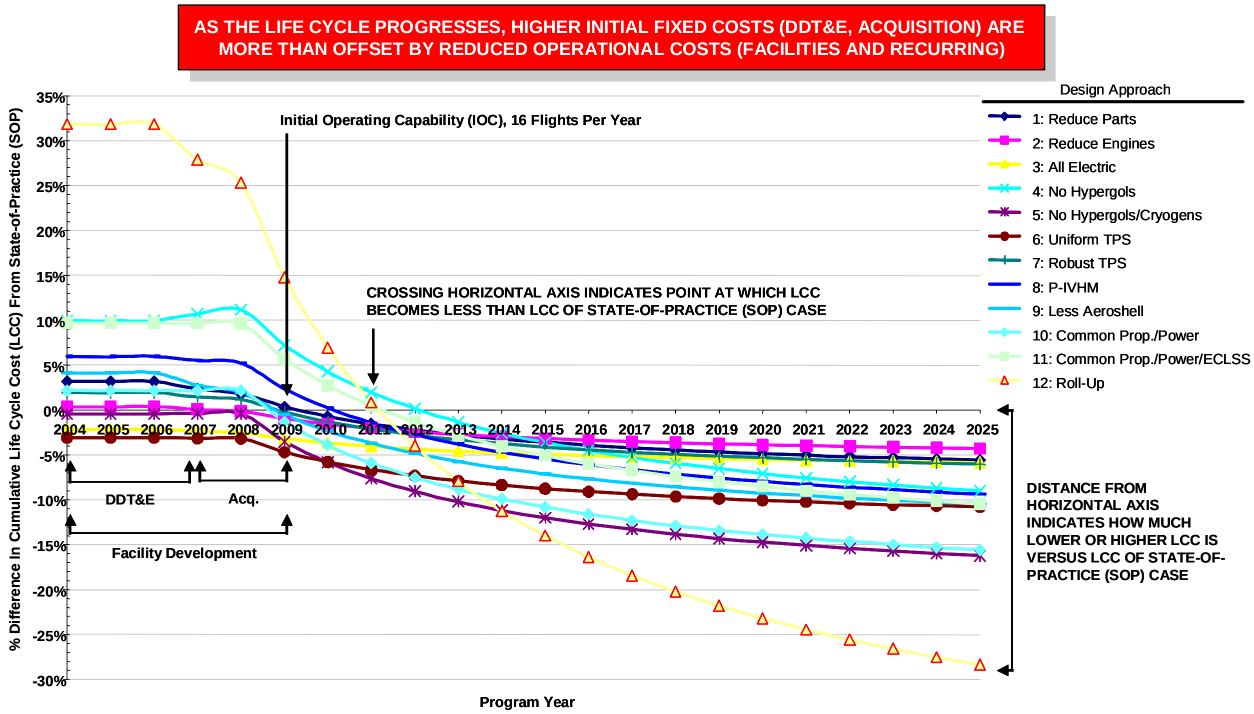
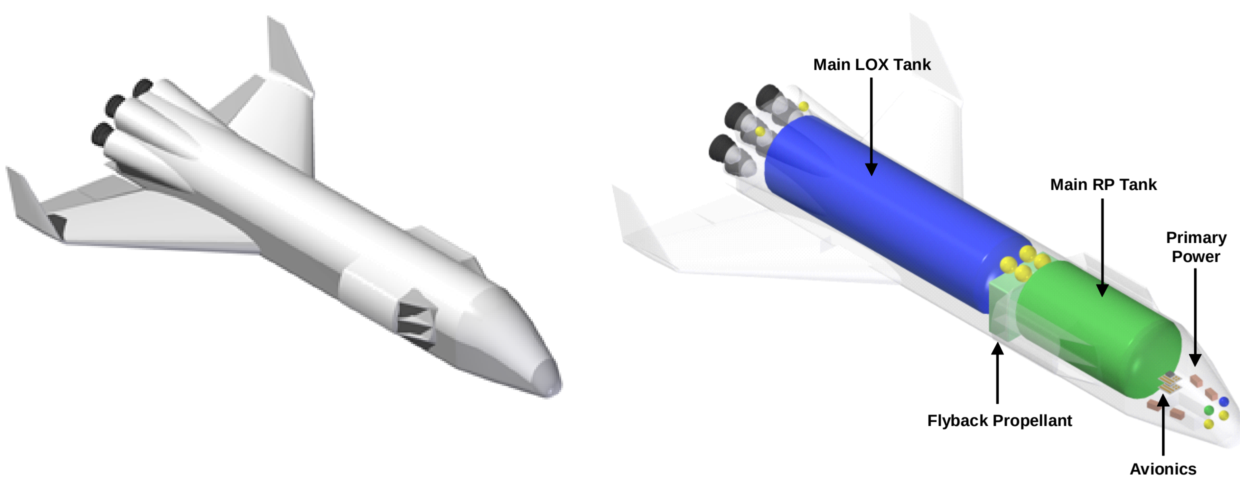
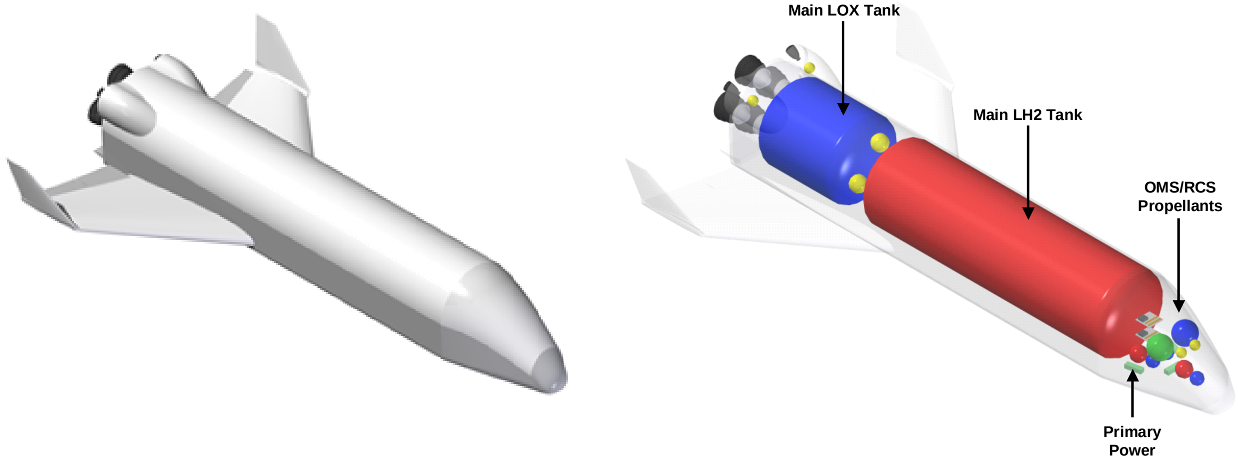


Fig. 8: D4Ops Context 1: Cumulative Life Cycle Cost Comparison to SOP (State-of-Practice).



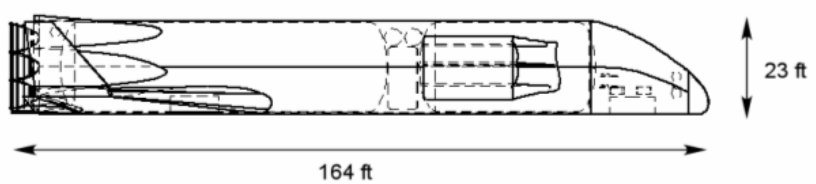
External View Internal Packaging View

Fig. 9: Mid-term Context 2 Booster Geometry and Packaging.



External View Internal Packaging View

Fig. 10: Mid-term Context 2 Orbiter Geometry and Packaging.



Design Specifications

Main Engine Type	RS-84
Main Engine Count	7
Dry Weight	472,856 lbs
Gross Weight	4,290,683 lbs

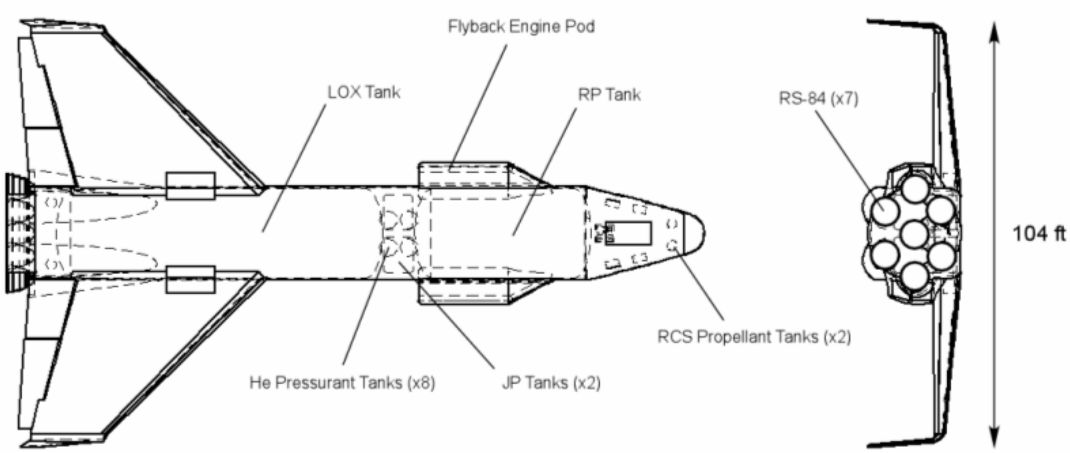
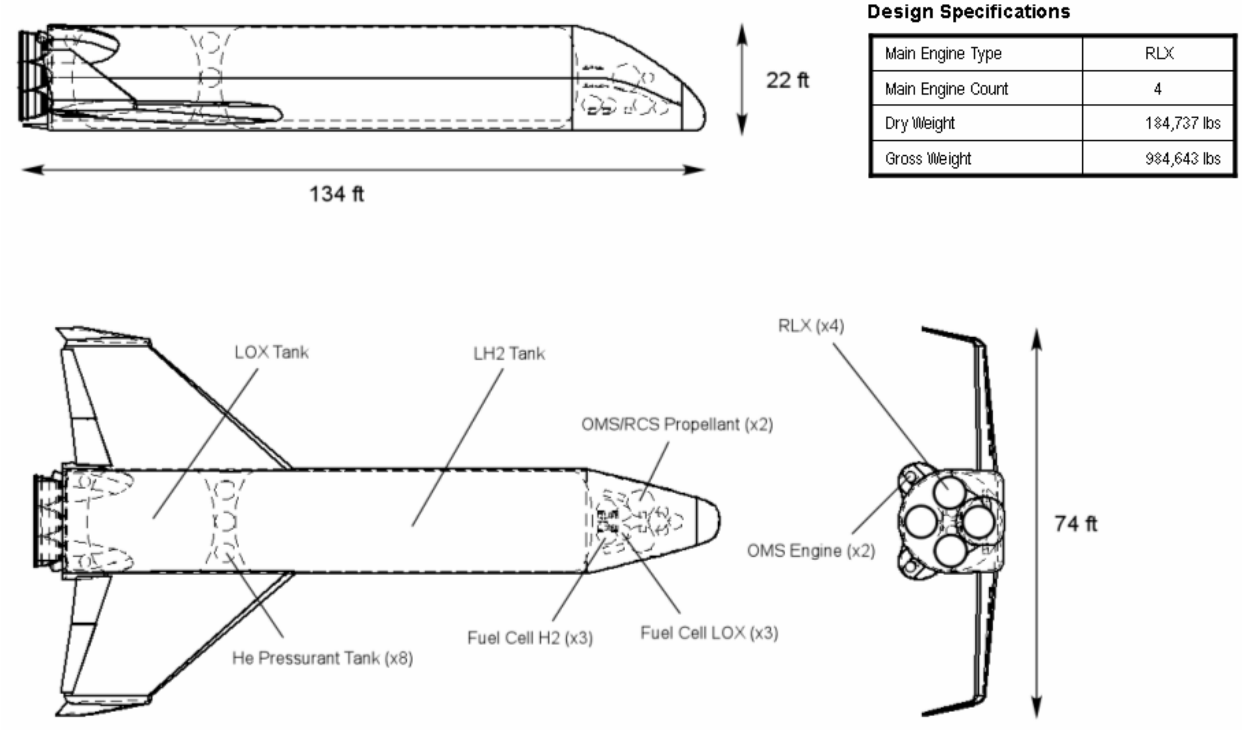


Fig. 11: Context 2 Booster Three-View: Design Approach 0 (SOP).



Design Specifications

Main Engine Type	RLX
Main Engine Count	4
Dry Weight	184,737 lbs
Gross Weight	984,643 lbs

Fig. 12: Context 2 Orbiter Three-View: Design Approach 0 (SOP).

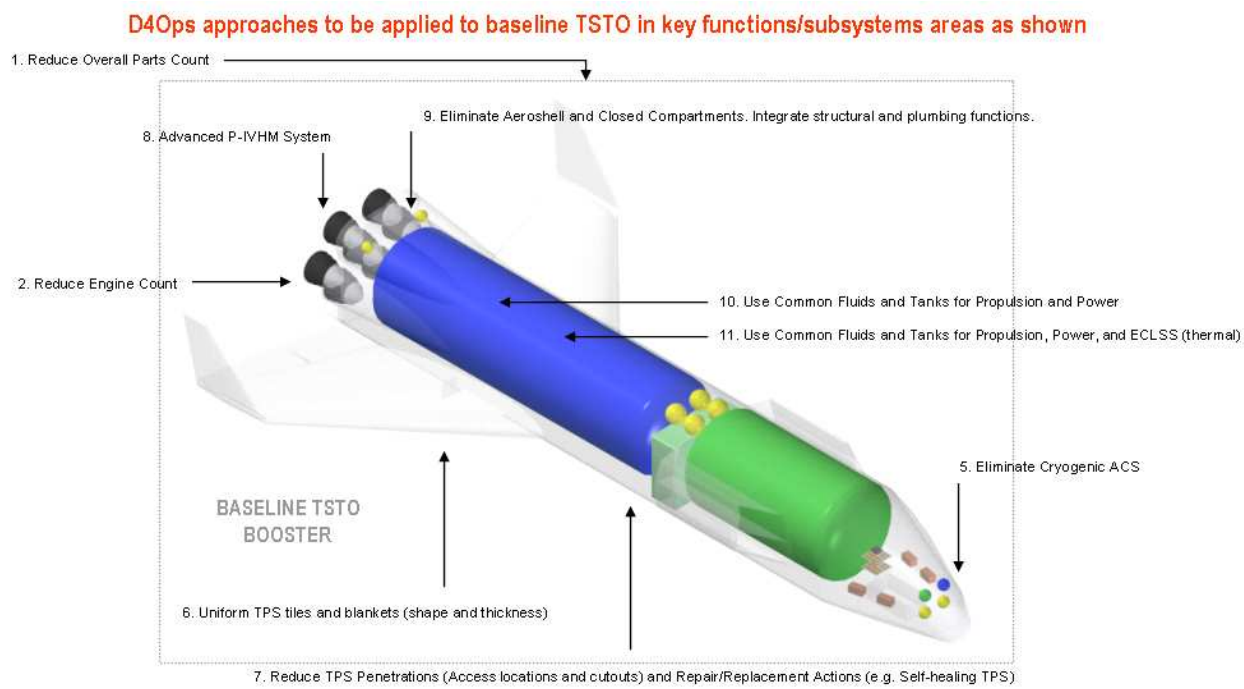


Fig. 13: Context 2 Booster: D4Ops Design Approaches to Be Added.

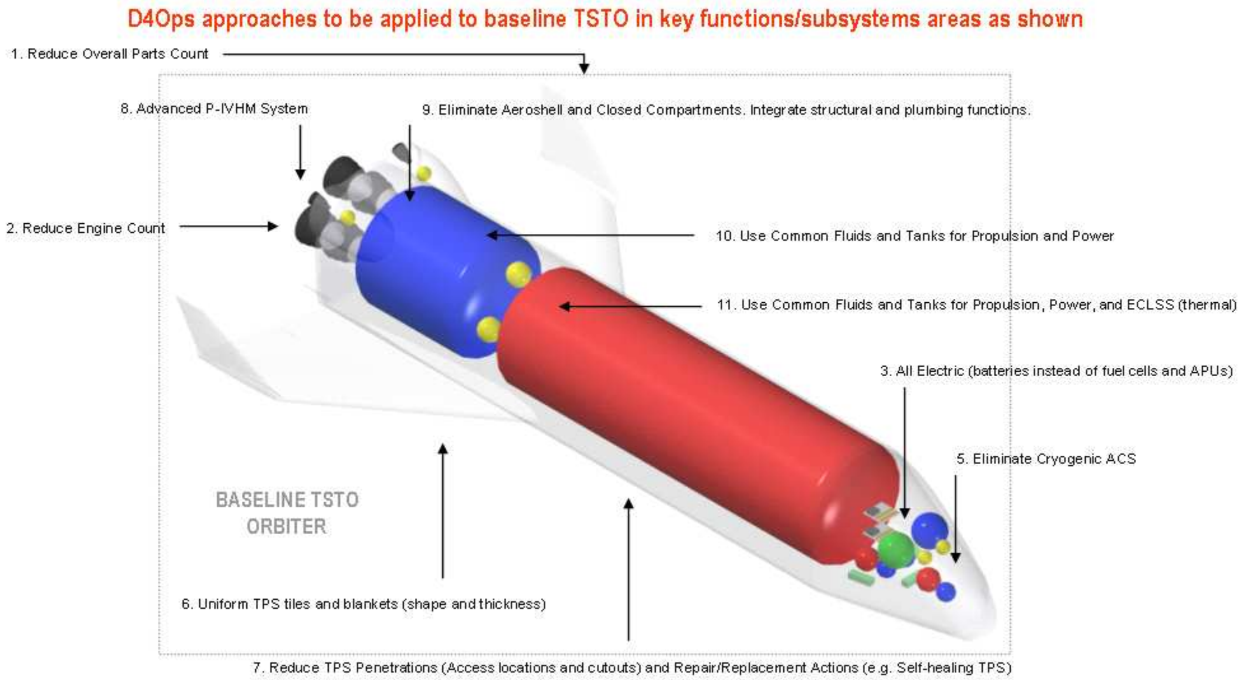


Fig. 14: Context 2 Orbiter: D4Ops Design Approaches to Be Added.

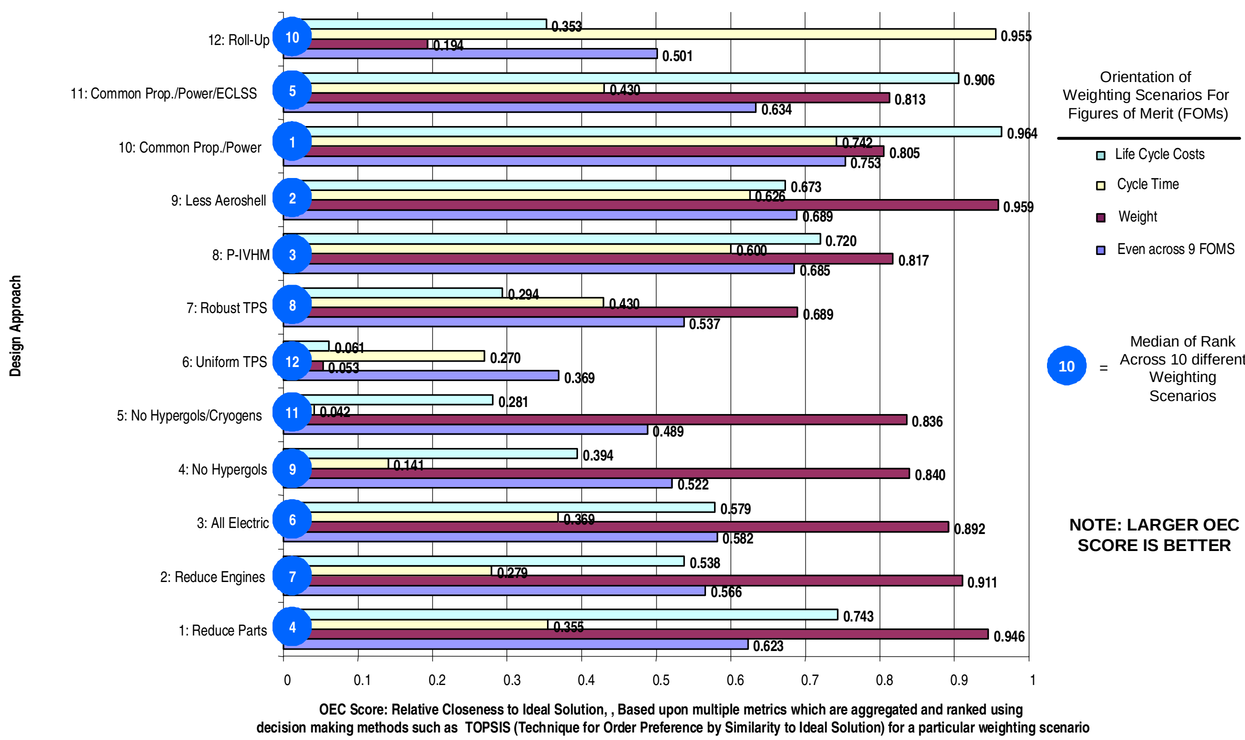


Fig. 15: D4Ops Context 2: TOPSIS Ranking of Design Approaches.

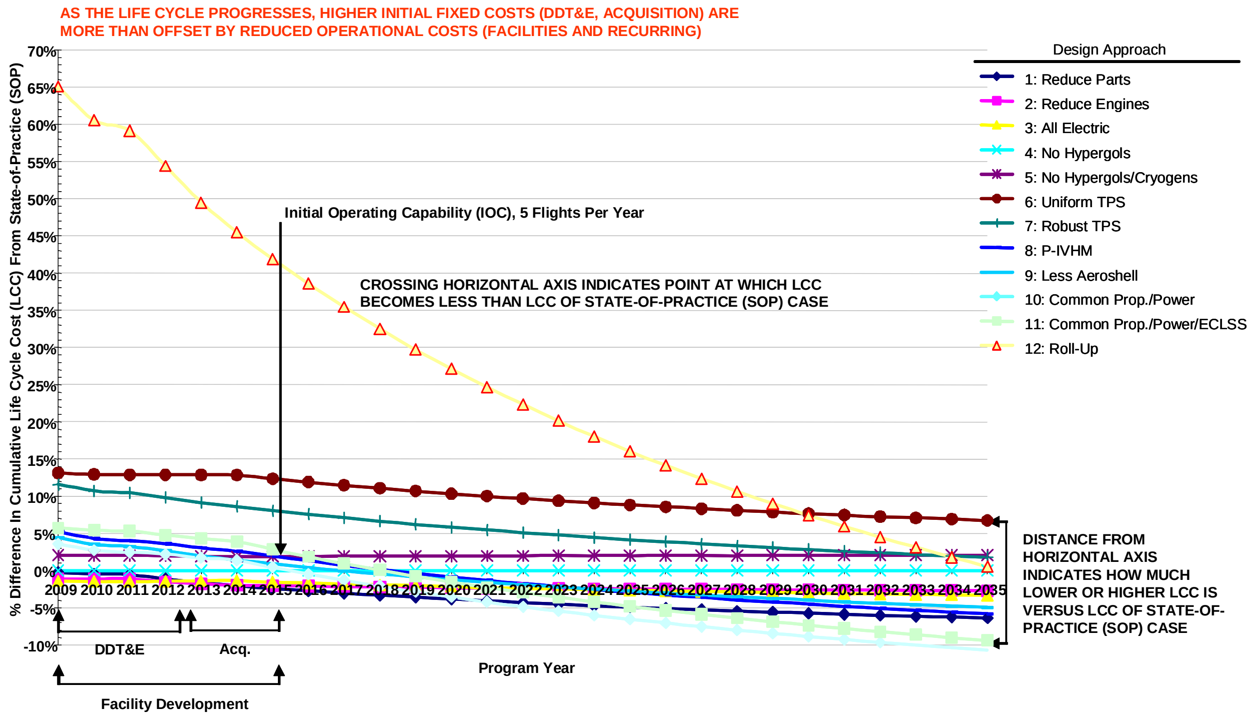
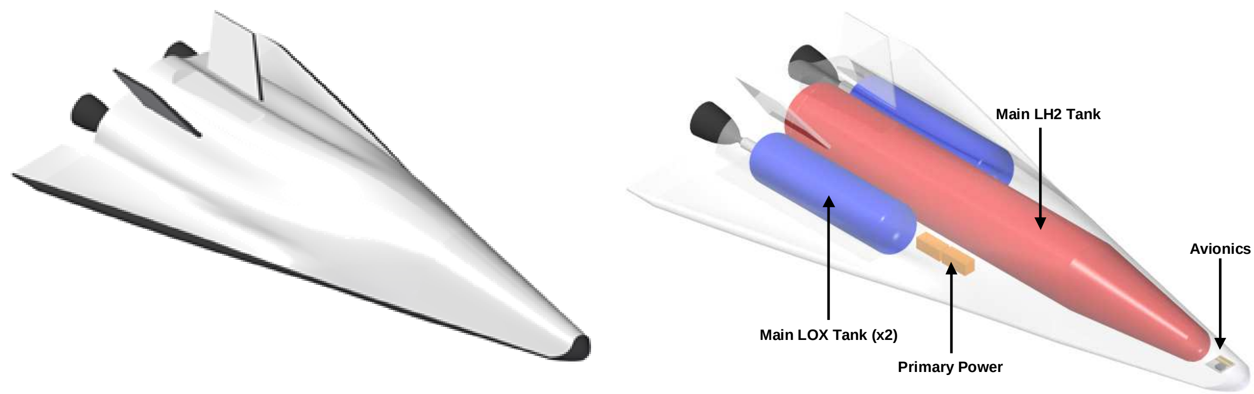


Fig. 16: D4Ops Context 2: Cumulative Life Cycle Cost Comparison to SOP.

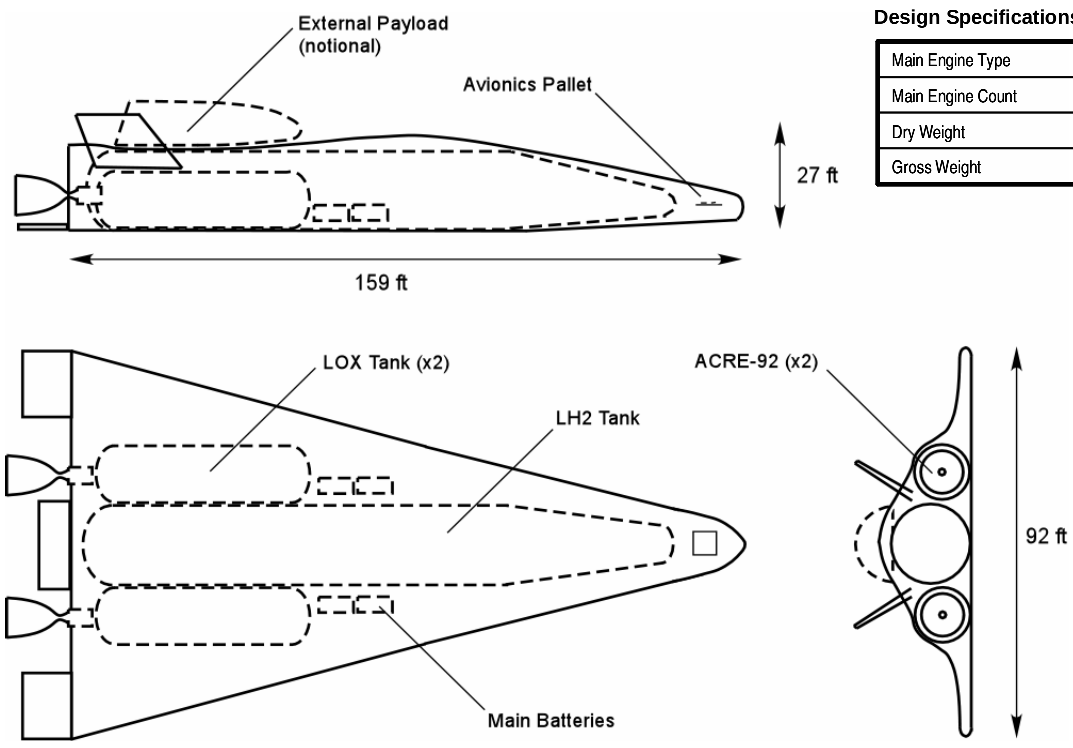
	Design Guideline	Description
CONFIGURATION	Incorporate Modular Design Approach	Locate propellant tankage and subsystems on pallet modules
	Fly Return Trajectory Inverted	Minimize windward TPS penetrations by re-entering atmosphere inverted
	Place LOX Tank Aft	If applicable, position LOX tank in aft end of fuselage in order to shorten or eliminate feedlines
PROPULSION	Utilize MPS with Improved Design Life	Main propulsion system should have improved design life compared with SSME in terms of duration and number of starts
	Reduce Main Engine Count	Reduce system complexity by reducing number of main engines (while increasing individual engine reliability)
	Reduce Likelihood of Gas / Liquid Leakage	Design connector and distribution systems to minimize risk of gas or liquid propellant leakage
	Design Accessible Propulsion System	Propulsion system components should be arranged to facilitate support and maintenance
	Avoid Using Center Engine	Avoid multi-engine designs in which a main engine is positioned in the center of a group of engines (poor access for engine maintenance)
	Reduce RCS Thruster Count	Reduce system complexity by employing fewer RCS thrusters than STS baseline (while simultaneously increasing the reliability of individual units)
	Use Non-toxic / Benign Propellants for OMS / RCS	Avoid chemicals such at hydrazine, MMH, and NTO to improve supportability and maintainability
STRUCTURES	Use Left / Right Symmetric TPS	Design mirrored TPS such that left and right TPS layouts are symmetric for a large percentage of the surface area
	Use Selectively-Uniform TPS Layout	Increase maintainability and supportability of TPS by using uniform (common shape/thickness) tiles or blankets on selected surfaces
	Reduce TPS Penetration Points	Design for minimal TPS penetration locations on vehicle. Use robust TPS design where penetrations are required
	Eliminate Closed Compartments	Remove aeroshell in selected areas to eliminate closed compartments and improve maintainability and supportability
MECHANICAL	Eliminate Hydraulic Systems	Use EMA / EHA systems for landing gear, aerosurface actuation, ect.
	Reduce / Eliminate Fuel Cells	Use high energy density storage batteries where possible in place of fuel cells to reduce complexity
	Incorporate P-IVHM	Include propulsion-focused IVHM system to improve ground checkout, safety, and maintainability
INTEGRATION	Use Common Fluids for Propulsion, Power, and Thermal Management	Design systems, tankage, and feedlines such that common fluids can be used for propulsion, power, and thermal management functions. Reduce number of unique fluids on vehicle to improve maintainability and supportability
	Integrate OMS / RCS Tankage and Hardware	Where possible, combine propellant tankage and hardware for OMS and RCS to improve supportability and maintainability
INTERFACES	Reduce Flight to Ground Interfaces	Design systems such that number of flight to ground interfaces is reduced compared with STS baseline

Table 2: Expanded List of D4Ops Design Approaches



External View   Internal View

Fig. 17: D4Ops Context 3a Geometry and Packaging.



Design Specifications

Main Engine Type	ACRE-92
Main Engine Count	2
Dry Weight	153,007 lbs
Gross Weight	1,317,749 lbs

Fig. 18: D4Ops Context 3a Three-view Drawing.

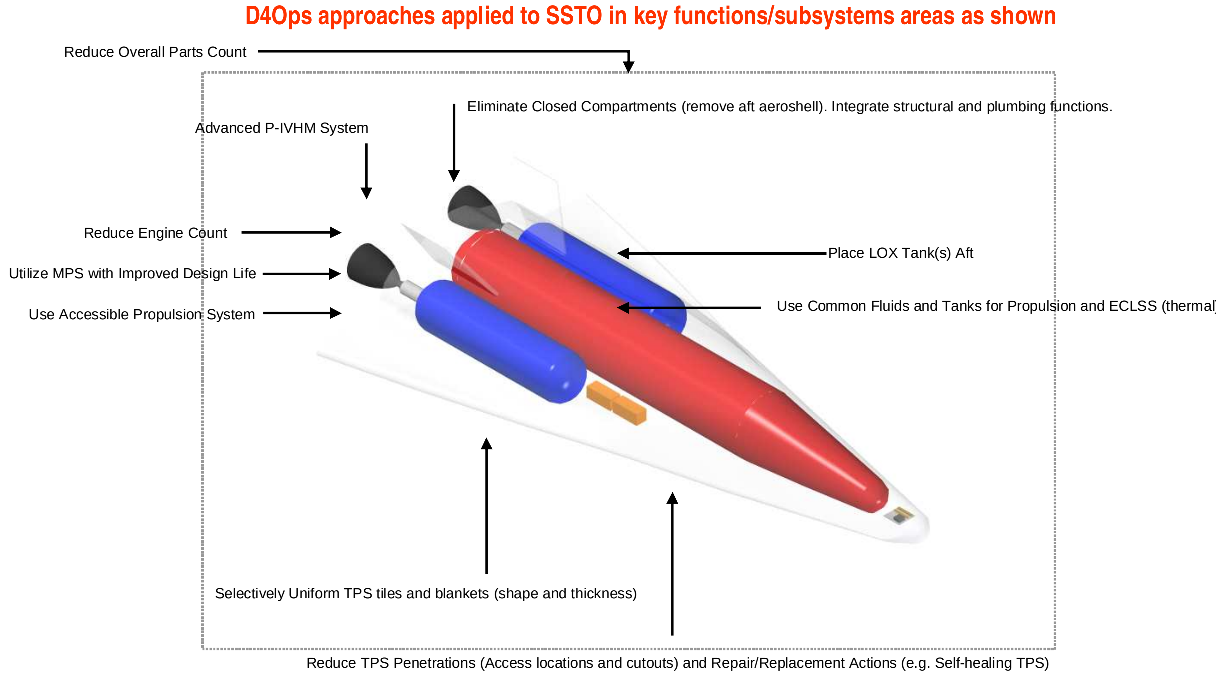


Fig. 19: D4Ops Design Approaches Included in Context 3a.

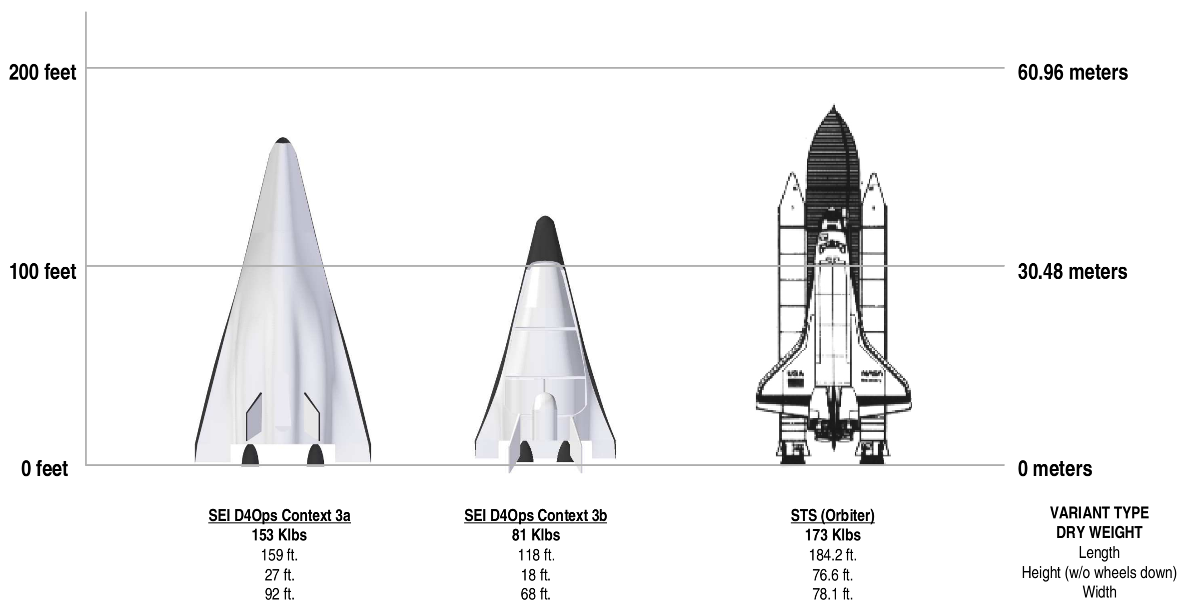
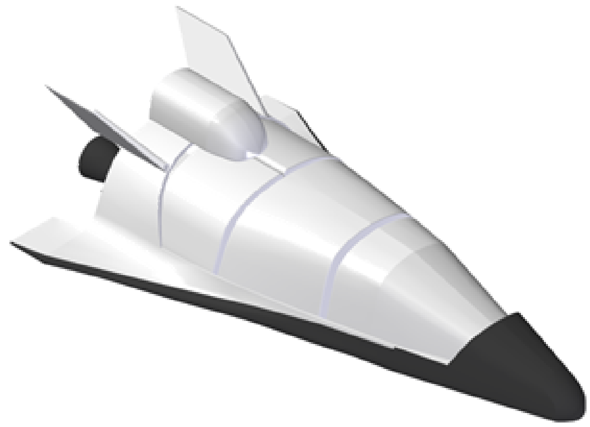
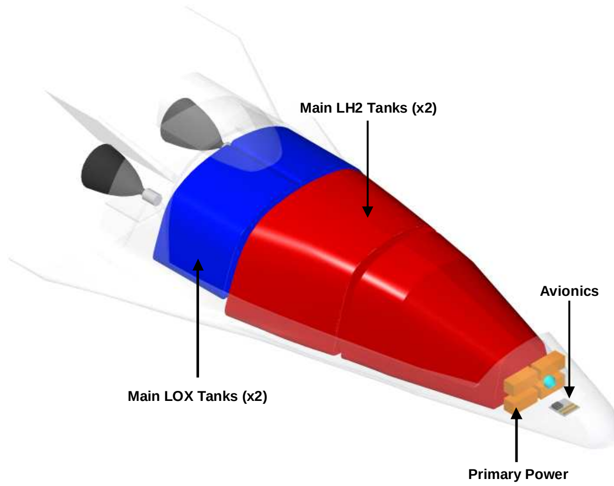


Fig. 20: D4Ops Context 3 Scale Comparison.

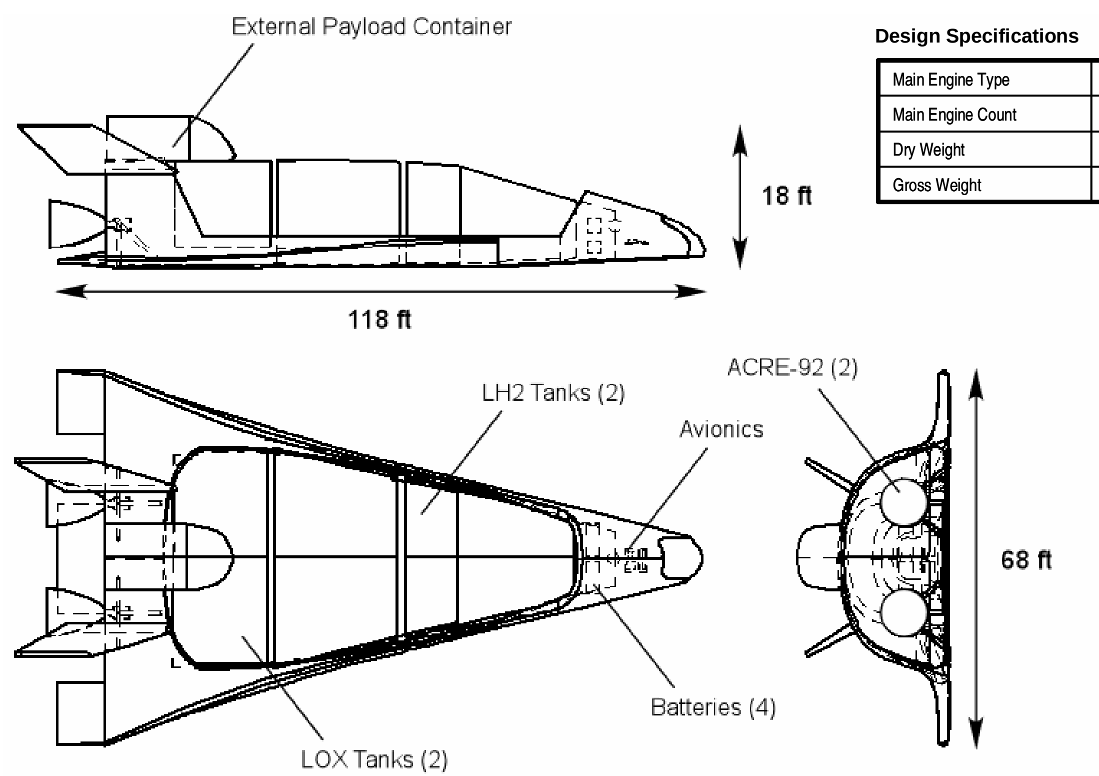


External View



Internal View

Fig. 21: D4Ops Context 3b Geometry and Packaging.



Design Specifications

Main Engine Type	ACRE-92
Main Engine Count	2
Dry Weight	81,617 lbs
Gross Weight	780,344 lbs

Fig. 22: D4Ops Context 3b Three-view Drawing.

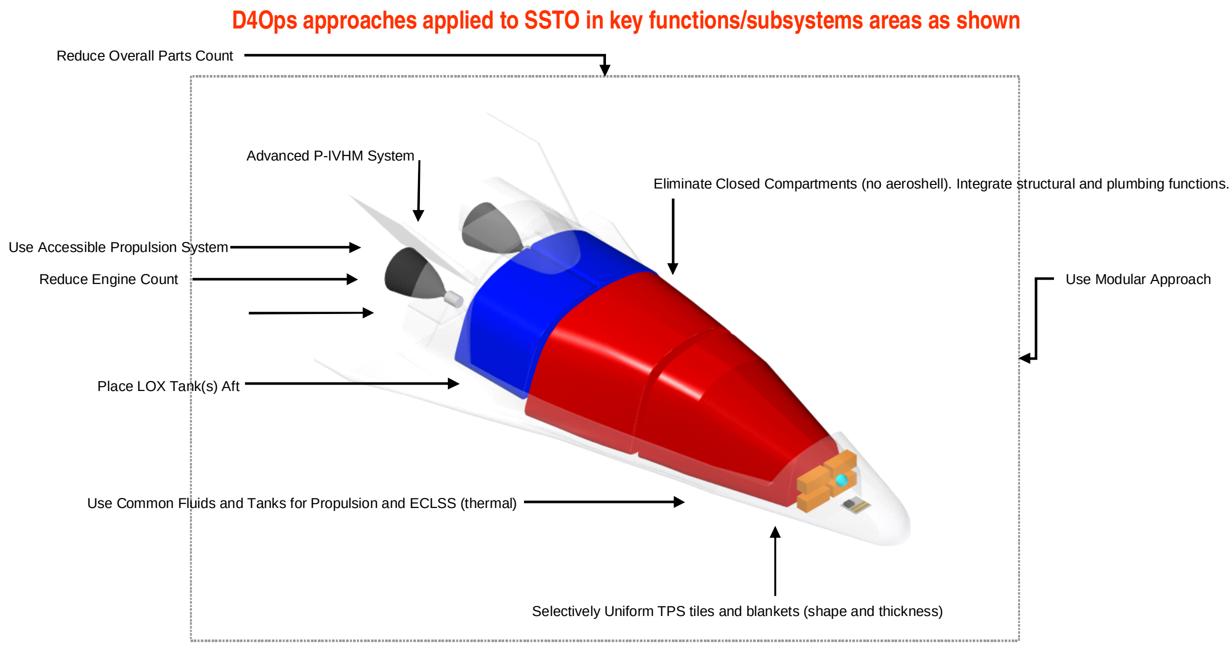


Fig. 23: D4Ops Design Approaches Included in Context 3b.